NUMERICAL - STATISTICAL PREDICTION
OF VISIBILITY AT SEA

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NAVAL POSTGRADUATE SCHOOL
Monterey, California

THESIS

NUMERICAL - STATISTICAL PREDICTION

OF VISIBILITY AT SEA

by

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March 1972

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ABSTRACT

Visibility is one of the most important weather elements in marine navigation. It is commonly believed that the primary factors determining visibility are the wind speed and the relative moisture content of the air. Using regression analysis, an attempt is made to establish a linear functional relationship between observed visibility and objectively-determined parameters from conventional marine surface observations. Forecast visibilities are obtained from derived regression equations using elements available from a numerical primitive equation forecast model.

Twenty-eight hundred observations in the North Atlantic were analyzed. It was determined that reliable regression equations were derived only from those observations obtained from ships with trained meteorological observers on board. The results indicate that numerical forecasts of surface temperature and humidity have not yet reached the accuracy necessary for use in this type of statistical prediction scheme.

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TABLE OF SYMBOLS AND ABBREVIATIONS

A	constant (7.5)
B	constant (237.3)
Dir	wind direction (degrees/10)
$T-T_d$	air temperature minus dew-point temperature (^oC)
e	ambient vapor pressure of the air (millibars)
e_s	saturated vapor pressure of the air (millibars)
e_w	saturated vapor pressure of the sea (millibars)
E	evaporation per 24 hours (meters)
V	wind speed (meters/second)
LAT	latitude (degrees × 10)
LONG	longitude (degrees × 10)
N	total cloud cover (tenths)
RH	relative humidity (hundredths)
T_d	dewpoint temperature (^oC)
T	air temperature (^oC)
T_s	sea water temperature (^oC)
$\mathbb{V}\cdot\nabla T_s$	$V\cdot\nabla T_s$ (meters ^oC/second)
VIS	meters or units of visibility code
WVT	total water vapor in the air column above the station (meters)

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I. INTRODUCTION

Visibility is one of the most important weather elements in marine navigation but it is one of the most complicated of all meteorological observations. The visual range is defined as the distance that an object can be seen [1]. The horizontal visual range near the surface is called the visibility. Prevailing visibility is defined as the highest visibility that is equalled or exceeded over sectors of the horizon which, when combined, total one-half or more of the horizon circle [2]. Prevailing visibility is the parameter reported by ships at sea.

At sea, the absence of objects at known distances makes the observation of visibility highly subjective. There, the appearance of the horizon, as observed from different levels, yields the best estimate of the prevailing visibility. The experienced seaman knows how difficult it is to estimate visibility at night. The presence of a "loom" around the ship's navigation lights is frequently an indication of deteriorating visibility. It has been estimated that the visibility in full moonlight is about 20% of the visibility in daylight in the same atmosphere [3].

There are several possible approaches to the problem of analyzing and forecasting visibility at sea on a large scale. Presently, visibility forecasts are prepared subjectively and are based on ship reports, air mass characteristics,

present and past weather, and climatology. Unfortunately, results are highly dependent upon the experience level of the forecaster. Some progress has been made in the area of modeling. However, the physical-dynamical models are based on microphysics and require input parameters on a scale that is not available from conventional marine surface observations. In this case, numerical generation of data from existing observations could be utilized.

Another approach seems worth trying for immediate operational use. A simple method is the application of statistical regression analysis based on objectively-determined observed and forecast parameters. This is the approach used in this paper. An attempt will be made to establish a linear functional relationship between the prevailing visibility and objectively-determined parameters available from conventional marine surface observations. Further, an extension will be made to obtain forecast visibility from elements available from numerical or other objective prognostic techniques.

II. BACKGROUND

A review of the available literature reveals much work of a general nature about fog prediction. However, relatively little research on the subject of sea fog was found and few attempts had been made to use a statistical approach. Schramm attempted to relate Fleet Numerical Weather Central's vapor pressure difference fields (saturated vapor pressure-ambient vapor pressure) and other available parameters to observed visibilities and it is his report that forms the basis for this paper [4].

The North Atlantic area was chosen as the locale to perform the analysis. This choice was based on climatology, density of observations, and the availability of previous research for comparison [5]. June and December 1971 were the selected periods of interest as climatology indicated a high percentage of low visibilities during these months. Input data for this research were obtained from the Fleet Numerical Weather Central climatology files.

The statistical resources of the W.R. Church Computer Center at the Naval Postgraduate School are many and varied. A stepwise linear regression program called BMDO2R was selected for the analysis [6]. Stepwise regression analysis enables the user to "build up" his regression equation from a simple linear to a multiple linear form by introducing one independent variable at a time.

III. PROCEDURE

A. DATA PROCESSING

The area of interest was further subdivided, based on climatology, for each of the two time periods. Figure 1 illustrates these areas. The three general areas chosen will be referred to herein as the Grand Banks area, the Norwegian Sea area, and the Station Ship area.

As the observations from the Ocean Station Vessels alone did not comprise a large enough data sample for each location, all reports within two degrees of the assigned station ship position were utilized. This was regrettable in that the Station Ship observations were desirable as a "control" input, to be compared with other observations in the same general area.

Marine surface observations for June and December 1971 were extracted from the Fleet Numerical Weather Central climatology files. These raw data are stored as received and are not processed prior to being stored on magnetic tape. A gross error check and rejection of duplicate observations was first performed on the data. Next, the following parameters were extracted:

1. Visibility (Vis)
2. Wind direction (Dir)
3. Wind speed (V)
4. Air temperature (T)

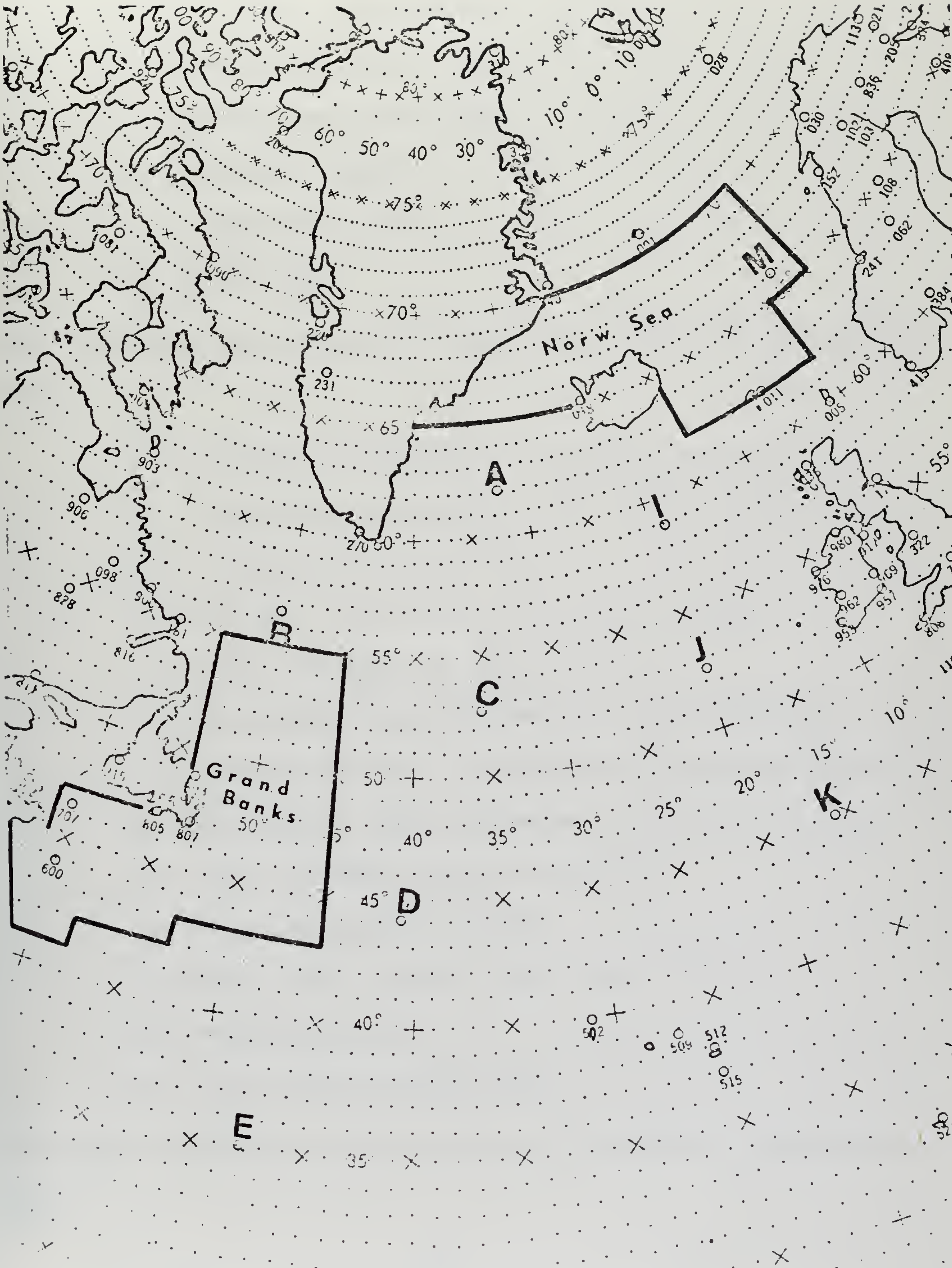

FIGURE 1

5. Sea surface temperature (T_s)
6. Dew point temperature (T_d)
7. Present weather code (WW)
8. Total cloud cover (N)
9. Latitude (LAT)
10. Longitude (LONG)
11. Date (DAY)

The following parameters were generated from the basic data above:

1. eastward component of the wind velocity (u)
2. northward component of the wind velocity (v)
3. dew-point spread ($T-T_d$)
4. air-sea temperature difference ($T-T_s$)
5. vapor pressure of the air (e_a)
6. saturation vapor pressure of the air (e_s)
7. saturation vapor pressure of the sea surface (e_w)
8. saturation vapor pressure difference (e_w-e_s)
9. vapor pressure deficit (e_w-e_a)
10. relative humidity (RH)
11. $V\cdot\nabla T_s$ for station ships only ($V\cdot\nabla T_s$)
12. evaporation (E)
13. total water vapor (WVT)

The vapor pressures were generated from Teten's expression [7]:

$$e(\text{mb}) = 6.11 \times 10^{\frac{AT}{B+T}} , \tag{1}$$

where T is temperature and A and B are constants. Dewpoint (T_d) and sea surface temperature (T_s) were entered for vapor pressure of the air and saturation vapor pressure at the sea surface, respectively. Laevastu [8] developed the following Dalton-type expression for evaporation:

If $(e_w - e_a)$ is positive:

$$E(m) = (0.26 + 0.077\ V)\ (e_w - e_a) \tag{2}$$

If $(e_w - e_a)$ is negative:

$$E(m) = (0.077V)\ (e_w - e_a) . \tag{3}$$

Total water vapor [9] was computed from a regression equation relating surface dew-point to total water vapor, shown below:

$$\ln WVT = -1.288 + 0.0384T_d \tag{4}$$

The Fleet Numerical Weather Central sea surface temperature analyses were used as input to obtain values of the gradient of the sea surface temperatures. Values of this gradient were then interpolated to the station ship positions and $\mathbf{V}\circ\nabla T_s$ computed.

All parameters except pressure terms were converted to the meter-kilogram-second (MKS) system of units. Over 2800 observations were utilized.

B. ANALYSIS OF THE DATA

Regression analysis is one of the most popular statistical tools in use. Stepwise regression enables the

researcher to exploit the power and speed of the computer to examine his data in much greater detail than straight multiple linear regression.

BMDO2R computes a sequence of multiple linear regression equations in a stepwise manner. At each step one variable is added to the regression equation. The variable added is the one which makes the greatest reduction in the sum of the errors squared. At each step of the process complete information is presented about the current regression equation. Initially, the program accepts up to 99 independent variables (predictors) and up to 9,999 cases.

For this study, the dependent variable, visibility, was entered in three forms:

1. Visibility in meters,
2. Visibility coded from ship reports, and
3. Natural log of the visibility code.

The independent variables were separated into two groups:

1. All available observed parameters (except present weather and cloud cover), and
2. parameters forecast by the Fleet Numerical Weather Central primitive equation model.

However, upon examination of the data from the primitive equation model, it was found that the forecasts of air temperature and vapor pressure were not useable, especially during periods of thermal instability. Consequently,

analyzed fields of surface temperature and vapor pressure were obtained.

No attempt was made to separate the observations with precipitation causing reduced visibility. Had this been done, the reduced sample size would have precluded any significant results.

A regression analysis was run for each area and for all combinations of observed independent variables and the three forms of the visibility. Forecast visibilities were then obtained by using the regression equations derived from the observed parameters. Two "forecast" visibilities were generated, one without the unuseable forecasts of air temperature and vapor pressure, but including all other parameters. The other "forecast" visibility entailed the use of analyzed fields of air temperature and vapor pressure with the remaining forecast parameters.

IV. RESULTS

Tables 1 through 11 illustrate the best results obtained using observed parameters for each area during the two time periods. The total number of observations used in the analysis for each particular area is shown. The coefficient of determinancy, R^2, can also be considered as the fraction of variance explained. In all cases an F-ratio greater than 2.25 indicates a level of significance greater than 0.95. Note that the standard error of estimate is expressed either in meters or units of the visibility code. The most significant variables are those that caused the greatest reduction in the sum of squares of the errors and are listed in decreasing order of importance. The derived regression equation with coefficients is also listed. The parameters are expressed in the MKS (meter-kilogram-seconds) system of units except for temperature ($^{\circ}$C) and pressure (millibars).

In general, less than one-half of the variance between the observed visibility and the visibility computed by the regression equation is explained. However, in nearly every case the F-ratio is large enough to indicate that a significant relationship exists. As an average of all cases, the following input variables are listed in order of importance as the most significant in reducing the sum of squares of the errors:

TABLE I

Area of Station Ship A

62N 33W

	June	December
Number of Observations	51	39
R	0.8612	0.7193
R^2	0.7146	0.5174
F-Ratio	8.170	2.631
Standard Error	0.7382	1.2749
Most Significant Variables	$T, RH, T-T_d, e_s$	$RH, T-T_d, V\cdot\nabla T_s, e_s$

Regression Equations

June: $Vis = 138.968 - 0.11343u - 0.02938v + 1.41320T - 0.04945T_s + 2.16727e_a - 3.65243e_s + 0.07573e_w - 0.04213E - 0.37952RH + 15.1393\, V\cdot\nabla T_s + 0.01211Dir - 0.08479V - 0.48006(T-T_d).$

December: $Vis = 98.864 - 0.07318u + 0.04174v - 0.38776T - 0.62250T_s - 2.5038e_a + 2.6594e_s + 0.18232E - 45.313V\cdot\nabla T_s - 0.01222Dir - 0.03958V - 0.66596(T-T_d).$

TABLE II

Area of Station Ship B

56.5N 51W

	June	December
Number of Observations	70	82
R	0.7018	0.5857
R^2	0.4925	0.3430
F-Ratio	5.117	3.323
Standard Error	5544 meters	0.9842
Most Significant Variables	$v, e_w - e_s, T_s - T$	$E, V, T - T_d$

Regression Equations

June: $\text{Vis} = -624933 - 74.8296u - 375.770v$

$+6687.87T_s + 5741.79(T_s-T) - 10482.2(e_w-e_s) - 485.580E$

$+ 7003.66RH - 171.426Dir - 203.656V + 38632.8(T-T_d)$

December: $\text{Vis} = 95.8679 + 0.02769u + 0.01104v$

$- 0.49935T + 0.49355e_w - 0.53794(e_w-e_s) + 0.60993E$

$- 0.14112RH + 45.8342WVT - 0.01723Dir - 0.21261V$

$- 0.39344(T-T_d)$.

TABLE III

Area of Station Ship C

52.7N 35.5W

	June	December
Number of Observations	76	63
R	0.7413	0.6086
R^2	0.5495	0.3704
F-Ratio	6.404	2.728
Standard Error	1.3073	4697 meters
Most Significant Variables	T_s, u, E, e_w, $V \cdot \nabla T_s$	e_a, E, V, $T_s - T$

Regression Equations

June: $Vis = 143.975 - 0.62642u - 0.19038v - 1.04475T + 13.4863T_s + 2.76753e_a - 15.3000e_w - 0.81309(e_w - e_s) + 0.81175E - 0.07947RH + 148.028V \cdot \nabla T_s + 0.19316Dir - 1.28930T_d$

December: $Vis = - 54141.4 + 27.7416u + 62.3268v - 2251.00T_s - 2433.96(T_s - T) - 14665.7e_a + 7168.23(e_w - e_s) - 1784.28E - 516.637RH + 769055.WVT + 82.1492Dir + 59.6531V.$

TABLE IV

Area of Station Ship D

44N 41W

	June	December
Number of Observations	81	101
R	0.7000	0.6747
R^2	0.4901	0.4552
F-Ratio	5.446	6.127
Standard Error	4777 meters	5057 meters
Most Significant Variables	$RH, T-T_d, T_s-T$	V, e_a, e_w-e_s

Regression Equation

June: $Vis = 159594. - 60.0878u - 156.446v + 942.632T_s - 6494.18(T_s-T) + 2891.01e_a - 2848.22e_w + 7416.06(e_w-e_s) + 306.969E - 1672.83RH + 27.3565Dir - 245.243V - 4486.08(T-T_d)$

December: $Vis = 45958.3 - 50.2461u + 114.716v - 6863.42T_s - 352.479(T_s-T) - 3071.13e_a + 10147.8e_w - 900.953(e_w-e_s) - 228.604E - 541.377RH + 32.0124Dir - 510.407V - 4331.01(T-T_d)$

TABLE V

Area of Station Ship E

35N 48W

	June	December
Number of Observations	78	103
R	0.6697	0.6518
R^2	0.4486	0.4248
F-Ratio	4.406	5.539
Standard Error	0.4446	0.6401
Most Significant Variables	u,V,RH,E	T_s,V,e_w,E

Regression Equations

June: $Vis = 85.3962 - 0.07962u + 0.01712u$

$+ 2.85741T_s + 0.09875(T_s-T) - 1.68866e_w - 0.07114(e_w-e_s)$

$- 0.08467E - 0.046262RH - 3.10378WVT + 0.01130Dir$

$+ 0.07057V - 0.13120(T-T_d)$

December: $Vis = 90.5714 - 0.01468u + 0.04646v$

$+ 5.34478T_s + 0.23113(T_s-T) - 3.8770e_w - 0.15234(e_w-e_s)$

$+ 0.20835E - 0.15799RH + 12.1009WVT + 0.00659Dir$

$- 0.14194V - 0.64965(T-T_d)$

TABLE VI

Area of Station Ship I

59N 19W

	June	December
Number of Observations	81	100
R	0.6773	0.5800
R^2	0.4587	0.3364
F-Ratio	5.316	5.070
Standard Error	0.9712	0.9143
Most Significant Variables	V,v,WVT,u	RH,u,V

Regression Equations

June: $Vis = 109.024 + 0.07426u - 0.05618v - 0.30439T - 10329T_s - 0.02041e_w + 0.09518E - 0.12608RH + 18.9350WVT - 0.01454Dir - 0.22802V - 0.37434(T-T_d)$

December: $Vis = 102.565 - 0.04026u - 0.37575T - 0.29355e_w + 0.05456E - 0.13815RH + 39.2677WVT + 0.02940Dir - 0.08429V - 0.14386(T-T_d)$

TABLE VII

Area of Station Ship J

52.5N 20W

	June	December
Number of Observations	71	100
R	0.5864	0.5616
R^2	0.3438	0.3154
F-Ratio	3.144	5.242
Standard Error	0.9874	6680 meters
Most Significant Variables	$T-T_d, V, e_w-e_s$	V,v,E

Regression Equations

June: $\mathrm{Vis} = 124.007 - 0.24223u - 0.15202v$

$+ 0.79758T_s - 3.62733(T_s-T) - 1.17777e_a + 3.07179(e_w-e_s)$

$- 0.19552RH + 36.3463V\cdot\nabla T_s - 0.15858V - 1.74012(T-T_d)$

December: $\mathrm{Vis} = - 5840.40 - 576.669u - 86.5089v$

$- 5577.52T_s + 6165.60e_w + 895.029E + 49965.9V\cdot\nabla T_s$

$+ 18042.2W\nabla T - 747.738V$

TABLE VIII

Area of Station Ship K

45N 16W

	June	December
Number of Observations	77	94
R	0.6410	0.6502
R^2	0.4109	0.4227
F-Ratio	4.603	6.079
Standard Error	1.2953	0.4749
Most Significant Variables	RH, e_s, u	RH, V, e_s

Regression Equations

June: $Vis = 144.747 - 0.15919u + 0.13870v - 2.02073(T_s - T) - 2.49072e_a + 1.92247e_s + 1.60880(e_w - e_s) - 0.41729RH + 0.00949Dir + 0.25229V - 3.84869(T - T_d)$

December: $Vis = 132.597 - 0.03920u - 0.02028v + 0.59468(T_s - T) + 1.45430e_a - 0.79227e_s - 0.42331(e_w - e_s) - 0.46488RH + 0.01406Dir - 0.01764V - 1.11553(T - T_d)$

TABLE IX

Area of Station Ship M

66N 02E

	June	December
Number of Observations	38	24
R	0.7656	0.8926
R^2	0.5861	0.7968
F-Ratio	2.950	4.278
Standard Error	0.4764	0.5764
Most Significant Variables	$(T-T_d), e_s, E$	e_a, $V \cdot \nabla T_s, T_d$

Regression Equation

June: $Vis = 112.891 + 0.14855u + 0.12889v - 2.18478e_a - 2.47101e_s - 0.11022(e_w-e_s) + 0.12234E - 0.16816RH - 23.5871\ V \cdot \nabla T_s - 0.00220Dir - 0.01236V - 0.43712T_d - 2.39449(T-T_d)$

December: $Vis = 138.993 + 0.25344u + 0.18560v - 8.87585e_s - 1.32500(e_w-e_s) + 0.67601E + 0.17117RH - 51.0598\ V \cdot \nabla T_s - 0.00608Dir - 0.24460V + 4.39060T_d + 4.98978(T-T_d)$.

TABLE X

Norwegian Sea Area

	June	December
Number of Observations	264	239
R	0.4475	0.4659
R^2	0.2003	0.2171
F-Ratio	5.737	5.22
Standard Error	0.9720	1.28
Most Significant Variables	$V, v, (T-T_d)$	$V, Dir, (e_w-e_s)$

Regression Equations

June: $Vis = 108.569 + 0.01895u - 0.07545v - 0.02328(T_s-T) - 0.42043e_a + 0.27283e_s + 0.01940E - 0.09583RH - 0.00781Dir - 0.11593V + 0.05253T_d - 0.65299(T-T_d)$

December: $Vis = 106.656 + 0.02474u - 0.02059v - 0.38857T - 0.04926T_s - 0.34881e_a + 1.03810e_w - 0.89120(e_w-e_s) - 0.12991E - 0.14243RH - 0.03066Dir - 0.03825V - 0.80111(T-T_d)$

TABLE XI

Grand Banks Area

	June	December
Number of Observations	501	383
R	0.3997	0.4206
R^2	0.1597	0.1769
F-Ratio	7.73	7.249
Standard Error	10,069 meters	7573 meters
Most Significant Variables	RH, v, $(T-T_d)$	V, u, (e_w-e_a)

Regression Analysis

June: $\text{Vis} = 73957.3 + 17.4662u - 263.223v + 654.609T_s - 1284.42e_a + 793.156e_s + 248.406e_w - 681.950E - 620.758RH + 70.4302Dir - 306.076V - 363.880T_d - 3138.57(T-T_d)$

December: $\text{Vis} = 50109.7 + 157.051u - 10.1304v - 1451.14T_s + 1398.67(T_s-T) + 792.729e_s - 179.374E - 193.697RH - 62066.2WVT - 509.609V + 1582.03T_d + 457.774(e_w-e_a)$

June

1. Dewpoint spread $(T_{\cancel{d}} - T_d)$
2. Relative Humidity (RH)
3. Windspeed (V),

December

1. Windspeed (V)
2. Relative Humidity (RH)
3. $\mathbf{V} \cdot \nabla T_s$

Forecast visibilities were generated using the primitive equation model parameters as input. As expected, results obtained using the full set of input parameters proved to be much more meaningful than results obtained without temperature, vapor pressure, and related parameters. Scatter-diagrams were constructed with the forecast visibilities; these indicate relatively little skill. The diagrams revealed the greatest errors to lie in the low-visibility range.

V. CONCLUSIONS

The primary parameters determining visibility at sea are wind speed and the relative moisture content of the air. This verifies G.I. Taylor's study of fog in the vicinity of the Grand Banks in 1917 and the results of Schramm in 1966 [10,1].

Based on the differences in regression equations at different Station Ships at different periods of time, a single regression equation would not be satisfactory over the entire North Atlantic. Further study based on Station Ship data only is necessary to determine the time, period, and areal extent over which a regression equation could be considered valid.

The lack of weight assigned to the $\mathbb{V} \cdot \nabla T_s$ parameter suggests that the gradient of the sea surface temperature was poorly defined in some areas. Undoubtedly important small scale features of the sea surface temperature field are smoothed out in the 63 × 63 grid size output of the Fleet Numerical Weather Central sea surface temperature analysis. This is in agreement with Laevastu's observations [11].

Correlation coefficients were higher in the cases where the majority of the observations were those from Station Ship data. A comparison of Grand Banks or Norwegian Sea correlation coefficients with any Station Ship area

verifies this fact. Further, the large percentage of explained variance (R^2) for Station Ship A in June is attributed to the fact that the majority of the observations are from the Station Ship. It can be concluded that estimates of visibility at sea by relatively untrained observers are not accurate. This suggests that a scalar analysis of observed visibilities would be of limited value except those made by trained observers. A visibility analysis based on the regression equations may prove to be of some use.

The results indicate that numerical forecasts of marine surface parameters such as temperature and humidity have not yet reached the accuracy necessary for use in this type of prediction scheme.

Given accurate observations of visibility at sea, such as those available from Station Ship data, reasonably reliable regression equations for visibility based on conventional marine surface observations are possible. Until such regression equations are derived and the quality of the numerical forecasts of the required parameters is improved, numerical-statistical prediction of visibility at sea can be used only as rough guidance by an experienced forecaster.

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13. ABSTRACT

Visibility is one of the most important weather elements in marine navigation. It is commonly believed that the primary factors determining visibility are the wind speed and the relative moisture content of the air. Using regression analysis, an attempt is made to establish a linear functional relationship between observed visibility and objectively-determined parameters from conventional marine surface observations. Forecast visibilities are obtained from derived regression equations using elements available from a numerical primitive equation forecast model.

Twenty-eight hundred observations in the North Atlantic were analyzed. It was determined that reliable regression equations were derived only from those observations obtained from ships with trained meteorological observers on board. The results indicate that numerical forecasts of surface temperature and humidity have not yet reached the accuracy necessary for use in this type of statistical prediction scheme.

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